

Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space

July 25 & 26, 2000
Sheraton Airport Hotel
Cleveland, Ohio

The goal of the workshop was to define specific and cross cutting research needs in the areas of thermal sciences and thermal engineering that will advance the state of knowledge to a level that will allow development of reliable and efficient heat transfer technology for space and extraterrestrial operations. Invited researchers and specialists in thermal sciences, thermal engineering and technical experts on the major space systems from academia, industries, national laboratories and NASA participated in the workshop. The plenary session presentations discussed the requirements, operating environments and constraints, heat transfer issues and challenges in the areas of:

- **Space power**
- **Propulsion and propellant**
- **In-situ resource utilization**
- **Life support systems**
- **Thermal management.**

The plenary session was followed by splinter sessions with the technical expert groups in respective areas. The splinter sessions had in depth discussion on the critical subsystems, components and the underlying thermal processes with the objective to identify critical gaps in knowledge and/or lack critical data needed for the design of reliable, efficient, low mass affordable systems. The reports generated by the technical expert groups are posted at <http://microgravity.grc.nasa.gov/6712/thermal/workshop.html> for your review. Please send your comments/questions on the technical group reports or any other aspects of the workshop to Dr. Mohammad Hasan at mohammad.hasan@grc.nasa.gov.

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POWER SYSTEM

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Driving “Requirements” Related to Microgravity

- Minimize system mass, area and volume
- Long life regenerative fuel cells (>10,000 hours)
- Heat pipe start up and operation
- Liquid metal reactor start up and operation (for Brayton or Rankine conversion cycles)
- Battery sensitivity to low-g –thermal driven gradients

Power Working Group

Research Areas (not in priority order)	AMTEC	Batteries	Fuel Cells	LMCR	Heat Pipes	Rankine Power Conversion	Brayton Power Conversion	Stirling Power Conversion
▪ Liquid metal melting/solidification				X	X	X		
▪ Two-phase and heat transfer (including liquid metals)								
- Flow regime prediction						X		
- Boiling heat transfer and evaporation	X		X	X	X	X		
- Condensation heat transfer	X				X	X		
- Phase separation			X			X		
- Flow instabilities			X			X		
- Interfacial phenomena			X		X	X		
- Two phase flow in porous media	X		X		X			
- Working fluid distribution	X				X			
- Wetting/de-wetting	X				X			
- Capillary flow issues			X		X			
▪ NC gas generation and management		X						
▪ Thermal gradients in re-charge batteries		X						
▪ Humidification and control			X					
▪ Materials compatibility (not gravity dependent)	X			X	X	X	X	
▪ Dust accumulation on radiators						X	X	X
▪ Systems models								

Propellants & Propulsion

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The discussion first started building a list of pertinent challenges

- Low Conductivity Supports
- Propellant Management Devices
- Gauging, Instrumentation
- Cryocoolers
- Low Mass MLI
- Active/Passive TVS
- Inert Gas Venting
- Composite Tanks

The discussion then refocused on open questions.

- Where is the liquid?
- How does thermocapillarity influence flow field in large tank?
- How does the liquid move?
- When is gravity an important variable?

The discussion finally organized around 5 topics:

1. Propellant Tank Pressure & Thermal Control
2. Propellant Transfer & Transient Effects
3. Fluid Flow & Heat Transfer in Large Tanks
4. Instrumentation
5. Fluid Flow & Heat Transfer in Pipes (collapsed into 2 & 3)

Propellants & Propulsion

1. Propellant Tank Pressure & Thermal Control

NEEDS:

- minimize tank/system mass
- scaling from small scale experiments to full scale tanks is not well known
- long duration missions

ENABLES:

- long duration missions
- lower mission costs
- decreased vehicle weight
- continuous functioning of fuel cells

CURRENT KNOWLEDGE:

- systems currently designed to avoid problems resulting in increased mass and power requirements
- understanding of processes is limited to small scale experiments or short duration systems in low-g
- large scale 1g data

Propellants & Propulsion

Propellant Tank Pressure & Thermal Control, Desired Improvements Cnt'd

Desired Improvements:

Systems

- systems capable of functioning for months/years instead of hours
- improved insulation or thermal barriers
- cryocoolers with improved efficiency and reliability
- improved active TVS systems

Better Understanding of Fundamental Processes

- interfacial heat & mass transfer; large scale, reduced g-level
- thermophysical properties (i.e. contact angle)
- thermocapillary convection in large scale tanks
- influence of higher-mode vibrational excitation
- knowledge of environment (i.e. insulation)
- influence of self-gravitation, gravity gradients, and gravity level

Cross-Cutting:

- ISRU, Life Support, Power, Space Science

Propellants & Propulsion

2. Propellant Transfer & Transient Processes

NEEDS:

- Resupply in reduced-g
- propellant depots
- possible support of Space Station
- pump cavitation prevention

ENABLES:

- very large vehicles
- long duration missions
- on-orbit assembly of vehicles and other structures
- orbit transfer vehicles
- space-based architecture

CURRENT KNOWLEDGE:

- experiment data is very limited, almost exclusively 1g or small scale
- design, analytical modeling, computational modeling is highly speculative
- capillarity/wetting behavior is at best known indirectly or imprecisely with data usually limited to small scale, non-cryogen, static experiments
- no data for flow with phase change and heat transfer in reduced-g

Propellants & Propulsion

Propellant Transfer & Transient Processes Cnt'd

Desired Improvements:

Systems

- better liquid vapor separation technologies or system performance immune to presence of phase mixture; should include single component systems and systems in which gas is a different substance (i.e. helium over H₂)
- optimized transfer systems including focuses on:
 - rapid transfer, efficient transfer, reliable transfer,
 - optimal tank & transfer system pre-conditioning/chilldown,
 - reusability, positive expulsion
- reliable content gauging and flow rate measurement

Better Understanding of Fundamental Processes

- condensation/evaporation at gas/liquid interface
- dynamic transients as process start/stops/proceeds
 - pressure collapse, flash evaporation, behavior near critical point,
 - water-hammer
- solubility of inert gases
- direct contact heat transfer
- fluid location and motion

Propellants & Propulsion

Propellant Transfer & Transient Processes Cnt'd

- heat transfer rates at solid boundaries
 - heat leaks, local dry out, film coefficients
- convective heat transfer in a reduced gravity environment
- thermal stratification

Cross-Cutting:

ISRU, Life Support, Power, Thermal Conditioning

Propellants & Propulsion

3. Heat Transfer & Fluid Flow in Large Tanks

NEEDS:

- predictable large vehicle dynamics (as it influences thermal performance)
- acceptable depot dynamics (as it influences thermal performance)
- pressure control
- efficient system/vehicle designs

ENABLES:

- large vehicles or other structures
- vehicles or other structures with large % mass in propellant

CURRENT KNOWLEDGE:

- same as listed for Transfer & Transient processes
- considerable knowledge base for storable propellants

Propellants & Propulsion

Heat Transfer & Fluid Flow in Large Tanks Cnt'd

Desired Improvements:

- almost anything listed under Transfer & Transient Processes

Systems

- fluid/solid interactions
 - slosh control/decoupling
 - baffles
 - compartmentalization
 - assorted internal structures and tank shapes

Better Understanding of Fundamental Processes

- slosh
- interactions with spinning vehicles
- wetting including influence of materials & surfaces
- influence of dynamics on contact angle including hysteresis

Cross-Cutting:

unique?

Propellants & Propulsion

4. Instrumentation

NEEDS:

- liquid/vapor sensors
- quantity gauging
- submersible pressure and temperature sensors
- low heat input sensors
- all of above should be accurate/reliable/long-life
- 1- and 2-phase flow rate sensors
- sensor integration with systems
- better calibration/standards

ENABLES:

- propellant transfer
- accurate control of spacecraft and systems
- accurate knowledge for mission execution
- failure detection; Integrated Vehicle Health Management (IVHM)
- increased life

CURRENT KNOWLEDGE:

- sensors for all these applications are available at some level of performance

Propellants & Propulsion

Instrumentation Cnt'd

Desired Improvements:

Systems

- see needs

Better Understanding of Fundamental Processes

- better basic technologies and techniques
- liquid persistence on sensors
- insensitivity to liquid wetting

Cross-Cutting:

Life Support, Life Sciences, Power, Commercial Satellites,
almost any system

Propellants & Propulsion

Working Group Comments:

- priority ranking and time horizon too dependent on NASA mission architecture and scheduling for working group to evaluate

ISRU Working Group-Summary of Research Topics by Priority Ranking

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1. Innovative Methods of Thermally Extracting Volatiles, Including Water, from the Moon, Mars and Asteroids
2. Rejection of Low Temperature Heat in the Hot Lunar Day
3. Extreme Cold Operations of Mechanical, Electrical and Fluid Systems
4. Innovative Lunar/Mars Concrete Processing
5. Heat Recovery from Processed Soil/Regolith
6. Evaluate Effects of Low-g on ISRU Processes That Involve Significant Heating
7. Evaluate Sintered Road Construction and Manufacture of Ceramic Building Materials
8. Evaluate Cold Trapping Processes for Recovery of Volatiles on the Moon.

Issues for Other Groups or Further Development

- Heat Rejection
- Thermal Coatings
- Sun Shields
- Insulation Materials
- Refrigeration
- Air Conditioning
- Thermal Management of All Systems
- Structural Stress from Thermal Effects
- Combustion in Low-g
- Thermal Issues Related to Drilling
- Heat Pipe Operations in Reduced Gravity
- Effect of Reduced Gravity on Propellant Storage Tanks
- Water Transfer and Storage in Extremely Cold Environments
- Freeze Protection

RESEARCH TOPIC: Innovative Methods of Thermally Extracting Volatiles, Including Water, from the Moon, Mars and Asteroids

Need: To develop thermal-based volatile extraction technologies that can be used to obtain important volatiles, especially water. Water is the key ISRU resource on the Moon, Mars, and in the Solar System.

Enables: A most cost-effective exploration program that fully uses the water resources available, for propellants, life support, chemical processing, concrete, etc.

Current Level of Understanding: TRL-1; See “The Lunar H₂/O Resource Use Program Plan”, developed under NASA/NIAC Research Contract 07600-021 by ORBITEC (report available on NIAC web site, see Rice – Author, 1999 reports).

Desired Improvements/Outcomes:

Near-term – Completion of analysis and modeling and hardware experimental simulations/Down-select of potential technologies for follow-on work

Mid-term – Flight demonstration/Proof-of-Concept

Long-term – Pilot plant leading to implementation/Utilization of extra-terrestrial hydrogen for exploration.

Cross-Cutting: A&R

RESEARCH TOPIC: Rejection of Low Temperature Heat in the Hot Lunar Day

Need: To develop thermal heat rejection methods to allow ISRU components (and other) that reject heat at < 100 C.

Enables: ISRU systems to properly reject heat.

Current Level of Understanding: TRL-2

Desired Improvements/Outcomes:

Near-term- Optimal design of thermal systems and experimental work/Effectively operating systems

Mid-term – Incorporation of these thermal system technologies into other flight experiments/Working systems

Long-term – Implementation/Working systems.

Cross-Cutting: Power Systems, Habitats, Cryogenic Storage Tanks

RESEARCH TOPIC: Innovative Lunar/Mars Concrete Processing

Need: To use ISRU-derived materials (e.g., cement, rock, sand, other fibers, and water) to construct low-cost structures for infrastructure for exploration bases, launch sites, roads and eventual colonization of the Moon and Mars.

Enables: Low-cost construction of infrastructure using pre-cast structures for a multitude of operations.

Current Level of Understanding: TRL-2; Small lunar concrete samples previously made with lunar material from Apollo by Dr. T. D. Lin has outstanding strength (twice that of conventional concrete). More work needs to be done to improve the processes and reduce the water content that ends up in concrete.

Desired Improvement/Outcomes:

Near-term – Develop technology in 1-g and test in 1/6 and 3/8 g, on ISS Centrifuge/Low-cost materials for infrastructure construction

Mid-term – Demonstrate process on the surface of the Moon/Confidence to support future planning and design activities

Long-term – Implement /Low-cost benefits.

Cross-Cutting – A&R, Space Transportation, Habitats, etc.

RESEARCH TOPIC: Extreme Cold Operations of Mechanical, Electrical and Fluid Systems

Need: To solve the problem of the anticipated extreme cold environment in the permanently shadowed cold traps of the Moon, other shadowed areas, night-time conditions, polar regions of Mars, etc. for robotic devices, miners, mechanisms, scientific measurements, and other devices. Areas of concern include bearings, lubricants, electrical motors, electrical components, computers, chips, contacts, rotating joints, conveyers, fluid lines, fluid valves, fluid regulators.

Enables: Ability to successfully conduct operations/missions.

Current Level of Understanding: TRL-2; US military has programs in cold regions that may apply. NASA and contractors may also have done work in this area.

Desired Improvement/Outcomes:

Near term – Conduct analysis and experiments in simulated conditions in 1-g. Consider KC-135 testing at 1/6 and 3/8 g/Solve problems and develop successful technologies

Mid-term – Use information and implement in designs/Improve reliability and success rates

Long-term – Implement / Successful missions.

Cross-Cutting – A&R

RESEARCH TOPIC: Heat Recovery from Processed Soil/Regolith

Need: To recover thermal energy from Moon/Mars/asteroid soils/regoliths during processing of volatiles and other materials in processing/mining machines.

Enables: Ability to successfully conduct energy-efficient operations/missions.

Current Level of Understanding: TRL-2; University of Wisconsin (Kulcinski/Wittenberg) have done extensive analytical modeling work on designs for helium-3 lunar miners.

Desired Improvement/Outcomes:

Near-term – Conduct analysis and experiments in simulated conditions in 1-g. Consider KC-135 testing also at 1/6 and 3/8 g/Develop useful approaches to minimize energy consumption

Mid-term – Use information developed and implement in designs/ Successful and workable designs

Long-term – Implement/Successful missions.

Cross-Cutting – A&R

RESEARCH TOPIC: Evaluate Effects of Low-g on ISRU Processes That Involve Significant Heating

Need: To evaluate the effects of low-g on ISRU processes that involve significant heating. There are a many different processes that can be used to develop ISRU products. Some of these ‘thermal’ processes may be significantly affected by the g-level. An assessment, followed by experiments should be conducted to determine the effects.

Enables: Ability to successfully conduct efficient process operations/missions.

Current Level of Understanding: TRL-1

Desired Improvement/Outcomes:

Near-term – Conduct analysis and experiments in simulated conditions in 1-g and consider KC-135 and ISS Centrifuge testing at 1/6 and 3/8 g/Develop workarounds, if needed, to allow success.

Mid-term – Use information and implement in designs/Successful system developments

Long-term – Implement/Successful missions.

Cross-Cutting – na

RESEARCH TOPIC: Evaluate Cold Trapping Processes for Recovery of Volatiles on the Moon

Need: To recover a fraction of the rocket engine exhaust (H_2O , CO_2 , etc.) near launch and landing pads. Also work in the technology area may also help understand the formation of the lunar polar water ice in the cold traps and support systems that may use cold trapping in process recovery approaches. An assessment, followed by experiments should be conducted.

Enables: Ability to successfully conduct efficient process operations/missions and potential for additional resource recovery.

Current Level of Understanding: TRL-1

Desired Improvement/Outcomes:

Near term – Conduct analysis and experiments in simulated conditions in 1-g. Consider KC-135 and Centrifuge testing at 1/6g/New techniques for volatile recovery

Mid-term – Use information and implement in designs/Successful technologies that contribute to ISRU needs

Long-term – Implement/Successful missions.

Cross-Cutting – Propulsion, other Surface Systems

RESEARCH TOPIC: Evaluate Sintered Road Construction and Manufacture of Ceramic Building Materials

Need: To evaluate the construction of sintered roads and manufacture of ceramic building materials on the Moon and Mars. Different mobile power systems need to be considered for road construction. An assessment, followed by experiments should be conducted.

Enables: Ground-based transportation via the ability to successfully and economically construct roads on the Moon and Mars and allows production of low-cost building materials.

Current Level of Understanding: TRL-1

Desired Improvement/Outcomes:

Near term – Conduct analysis and experiments in simulated conditions in 1-g. Consider KC-135 and Centrifuge testing at 1/6 and 3/8 g/New useful technology developed

Mid-term – Terrestrial demonstrations/Success in improved low-dust ground transport systems and infrastructure construction

Long-term – Implement/Successful missions.

Cross-Cutting – Surface Systems and Vehicles, A&R, Habitats, etc.

RESEARCH TOPIC: ISRU Component and Subsystem Operational Characteristics

Needs: All ISRU chemical plants composed of several/many components. ISRU systems will sometimes require the assembly of complex components and subsystems that are designed and optimized with respect to different criteria and environments than most terrestrial process technologies. This task area contemplates the development of operational characteristics, through modeling and experimentation, for advanced ISRU components and subsystems, in terms of the heat, mass and momentum transport phenomena associated with these components and subsystems. This includes very basic unit operations (such as pumping and compressing) where the operational characteristics of the components performing these unit operations are not already known, plus complex coupled phenomena including, in some cases, chemical reactions and separations.

Enables:

Current Level of Understanding: TRL 1-5

Desired Improvements/Outcomes:

Near-term-Experimentation and modeling for an initial set of ISRU components.

Mid-term- Completion of experimentally coupled operation characteristics for a broad set of ISRU components. A flight demo of an ISRU system that produces propellant and oxygen from the Martian atmosphere.

Long-term- Utilization of ISRU components and subsystems for robotic missions.

Outcome- Improvements Produced by New Understanding:

Cross-Cutting: Robotics, Avionics, Power Generation

RESEARCH TOPIC: Modeling of Complex High Temperature ISRU Transport Processes and Development of Scaling Laws

Needs: A number of high-temperature ISRU processes involve several complex coupled transport phenomena, including combined radiation and convection heat transfer, mass transfer, reaction kinetics, etc. Because these coupled phenomena are generally non-linear, the scale-up of component hardware from bench-top or small flight demos, to full-scale hardware for manned missions, will require non-linear scaling relationships. Specific needs are:

- Production of propellants and consumables on Mars and the Moon
- Solid Oxide (zirconia) electrolysis
- Hydrogen reduction
- Thermal reduction of regolith.

Enables:

Current Level of Understanding: TRL 3-4

Desired Improvement in Understanding:

Near-term Develop models and verify model validity with bench top experiments. The models should include all modes of heat transfer, reaction kinetics, and mass transfer.

Mid-term Validate the models using flight demonstrations and develop scaling laws.

Long-term Use scaling laws to design and build large scale systems for HEDS needs.

Outcome: Improvements produced by new understanding:

- Improved performance leading to reduced mass and power requirements.
- Greater fidelity in the performance of designed equipment.

Cross-Cutting:

Technologies are also common to life support, so developed scaling laws should be transferable to life support components.

RESEARCH TOPIC: Development of Accelerated Testing and Modeling Protocols for Ensuring High Reliability of ISRU Components, Sub-systems, and Systems

Needs: Initial useage of ISRU components and subsystems will not be proceeded by ten's of thousands of hours of operation to reliably identify failure rates and the most likely failure modes, etc. For example, hign temperature processes such as zirconia electrolysis and certain chemical reactors (e.g. reverse water gas shift) may have to be thermally cycled on a daily basis and will have to be designed and operated so that startup procedures and daily use do not compromise their materials of construction. However, initial flight demonstrations and usage of these hardware items will likely precede the development of extensive operating experiences. Protocols and standards for design, testing, and modeling of ISRU components and subsystems in order to ensure high reliability during use are needed. Examples are: solid oxide (zirconia) electrolysis and reverse water gas shift reactors

Current Level of Understanding: TRL ?

Desired Improvement in Understanding:

Near-term Preliminary selection of design, testing, and operating protocols for typical high temperature ISRU components. Initial failure investigations underway.

Mid-term Completion of initial failure model studies for selected operating protocols.

Long-term Develop a comprehensive database that can be used for various ISRU systems.

Outcome- Improvements Produced by New Understanding:

Cross-Cutting:

Avionics, Life Support Systems, Reuseable Propulsion Systems

RESEARCH TOPIC: Development of High Temperature Insulation materials to reduce Heat Transfer Losses and Thermal Cycling of ISRU Components

Needs: A number of high temperature ISRU processes require high temperature operation (200 to 1000+°C) for high efficiency and reduced mass, volume reasons. Minimizing start-up time to get to operating temperature, improving efficiency at steady state operation would benefit from improved high temperature insulation materials. In addition, these low thermal conductivity materials could lessen the thermal cycling shock to components shut-down during night time or other non-use periods such as in transit operations, or at least minimize the maintenance heater power requirements for components that cannot tolerate thermal cycling. Examples are:

- Sabatier reactors
- Solid Oxide (zirconia) electrolysis
- Reverse water gas shift reactors
- Extraction of volatiles from regolith

Current Level of Understanding: Very mature MLI technology (TRL 8-9) exists for low temperature insulation for cryogenic storage applications. But relatively low maturity (TRL 2) exists for high temperature insulation (mainly SOA aerogels).

Desired Improvement in Understanding:

<u>Near-term</u>	Investigate and measure properties of SOA materials in expected environmental conditions. Perform modeling and development of promising new materials/composites.
<u>Mid-term</u>	Fabricate and test new materials in expected environments using bench-top level experiments.
<u>Long-term</u>	Test in ground-based components in environment chambers. Implement in flight demo or full-scale component.

Outcome- Improvements produced by new understanding:

<u>Near-term</u>	Establish database of thermal conductivity data for SOA material at ISRU component specific conditions.
<u>Mid-term</u>	Achieve 5x to 10x improvement in thermal insulation by means of new materials developed.
<u>Long-term</u>	Demonstrate 10x + reduction in heat loss in ground-based testing of ground-based or flight demo component.

Cross-Cutting: High temperature dynamic power systems (nuclear, solar), high temperature propulsion (nuclear, solar thermal)

NOTES:

Additional items
Asteriods

Heat transfer coefficients on Mars
Reference Dead state on Mars

Heat Transfer Scaling issues of small to large ISRU systems (high temperature multi-mode of heat transfer)

Life Support Flow With Phase Change

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Needs that drive research

- μ g condenser
- evaporator
- water purification
- temperature/humidity control
- urine processing
- food storage (refrigeration)
- material processing

Current Level of Understanding

- empirical data for specific configurations
- boiling in tubes – some models
- boiling on wire – data available

Life Support

Flow With Phase Change Continued

Desired Outcome (improve understanding)

Near Term (N)	Heat transfer effectiveness prediction
Mid Term (M)	Fluid flow topology
Mid Term (M)	Quantification of non-condensing gas effects
Long Term (L)	Scale rules for fractional gravity
Long Term (L)	Non-equilibrium and coupled effects on flow

Benefits

- Optimized design
- Improved effectiveness
- System reliability

Cross Cutting

- ISRU
- Thermal Management
- Power

Emerging/Alternate Technologies Applicable to Life Support

Needs that Drive the Topic

- Improving system performance
- Reduced weight, power, volume
- Thermo acoustic systems
- Flow control with:
 - Electric fields
 - Acoustics
 - Magnetic
 - Active geometry
- Microchannel reactors and heat exchanges

Current Technical Base

- Feasibility testing under 1'g'

Desired Outcome – (Improved understanding)

- M Understanding fundamental physics of processes
- N Determine gravity independence
- L Test Life Support applications

Emerging/Alternate Technologies Applicable to Life Support Continued

Benefits

- Reduced gravity effects
- Improved system performance

Cross-cutting

Terrestrial applications

Life Support

Multi-Phase Flow in Packed Beds

Needs:

- Water processing – catalytic beds
- Bio reactors – reduced expendables

Current Knowledge Base:

Empirical data

Models for 2 ϕ flow in pipes

Desired Outcome (Improvements)

- M Development of flow regime map
- N Pressure drop prediction
- N Gas/Liquid Distribution
- L Math model – predictive
- L Addition of chemical reaction to model

Life Support Multi-Phase Flow in Packed Beds Continued

Benefits:

- Optimized design
- Reduced bed size
- Reliability improvement
- Reduced development cost

Cross-cutting:

- Commercial chemical bed design
- ISRU

Thermal Management

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- Capillary Devices(loop heat pipes(LHP), capillary pumped loops(CPL))
 - Needs: Lack of detailed understanding of capillary devices precludes new designs for new applications in a cost-effective manner
 - Current LOU: General empirical understanding of how these devices work under steady state conditions
 - Desired Improvements:
 - **Near:** CPL start-up (which includes pressure spike), boiling incipience,vapor (bubble) growth, porous media transient vapor and liquid flow.
 - **Mid term:** LHP hysteresis, miniaturization(scaling), complex geometries, high flux, conductance
 - **Long term:** supercapacity wicking structures, very large devices, nano devices
 - Outcome:
 - **Near:** greater reliability and system safety ,on-demand operation, better knowledge of design margin

Thermal Management, Continued

- **Mid term:** new applications for CPL, LHP.
- **Long term:** new applications possibly eliminating mechanical pumps (e.g. 3rd Gen RLV)

–Approach:

- 1) Instrumentation and Flow Visualization
- 2) Phenomenological/Analytical/Computational based on ground and space-based experiment observation (e.g. Mars G, Moon G, Microgravity)

–Cross Cutting: Power (fuel cell fluid management) ISRU, Propellant

Thermal Management

- **Non** - Capillary Devices(mechanical, vapor, electrohydrodynamic, etc.)
 - Needs: Need to dissipate high heat fluxes and/or high power levels (e.g. > 100 kW)
 - Current LOU: Very limited understanding of flow regimes, pressure drops and heat transfer (boiling and condensation) under reduced gravity of varying gravity conditions, phase separation. No understanding of burnout (CHF),especially low velocity flows required for low pressure drop.
 - Desired Improvements/Outcome:
 - **Near:** several hundred W/cm²
 - **Mid term:** several hundred W/ cm²
 - **Long term:** flexibility to design high performance cooling systems for a variety of fluids and packaging geometries
 - Approach:
 - 1) Instrumentation and Flow Visualization up to and including burnout
 - 2) Phenomenological/Analytical/Computational based on ground and space-based experiment observation (e.g. Mars G, Moon G, Microgravity)
 - Cross Cutting: ISRU, Propellant, Life Support

Thermal Management

- **Other Topics-**

- Scaling
- Variable G Environments
- Closer Collaboration between Universities, Government and Industry; Joint research effects on critical technologies
- Explore the extremes in fluid property variation ranging from cryogenic to liquid metals
- Miniaturization (nano- meso- micro)
- Cryogenic Maintenance, Cryogenic Fluid Management
- Phase change materials (solid-liquid) for transient energy thermal management
- Enhanced Student participation in NASA research projects
- Incorporate microgravity thermal considerations early in thermal design.